



Evaluation of the Effect of Cr, Mo, V and W on the Selected Properties of Silumins

T. Szymczak^{a, *}, J. Szymshal^b, G. Gumienny^a

^a Department of Materials Engineering and Production Systems, Lodz University of Technology, Stefanowskiego 1/15 Street, 90-924 Łódź, Poland

^b University of Occupational Safety Management in Katowice, Faculty of Technical Sciences, Poland Bankowa 8 Street, 40-007 Katowice, Poland

* Corresponding authors. E-mail address: tomasz.szymczak@p.lodz.pl

Received 22.05.2018; accepted in revised form 29.10.2018

Abstract

The results of statistical analysis applied in order to evaluate the effect of the high melting point elements to pressure die cast silumin on its tensile strength R_m , unit elongation A and HB were discussed. The base alloy was silumin with the chemical composition similar to EN-AC 46000. To this silumin, high melting point elements such as Cr, Mo, V and W were added. All possible combinations of the additives were used. The content of individual high melting point additives ranged from 0.05 to 0.50%. The tests were carried out on silumin with and without above mentioned elements. The values of R_m , A and HB were determined for all the examined chemical compositions of the silumin. The conducted statistical analysis showed that each of the examined high melting point additives added to the silumin in an appropriate amount could raise the values of R_m , A and HB. To obtain the high tensile strength of $R_m = 291$ MPa in the tested silumin, the best content of each of the additives should be in the range of 0.05-0.10%. To obtain the highest possible elongation A of about 6.0%, the best content of the additives should be as follows: chromium in the range of 0.05-0.15%, molybdenum 0.05% or 0.15%, vanadium 0.05% and tungsten 0.15%. To obtain the silumin with hardness of 117 HB, chromium, molybdenum and vanadium content should be equal to about 0.05%, and tungsten to about 0.5%.

Keywords: Mechanical properties, Statistical methods, Multi-component silumins, Pressure casting

1. Introduction

Aluminium alloys are the second after iron alloys material most often used in the production of castings [1-3]. Silumins are the most widespread representatives of cast aluminium alloys. Due to their low specific gravity, they are willingly used for the production of structural elements that require high relative strength. In practice, their properties are usually improved by refining of alloy melt [4], modification [5] or intensification of the cooling process [6]. Magnesium and/or copper alloys are often subjected to precipitation hardening, which consists in supersaturation and subsequent aging [7-10]. The use of high melting point elements like Cr, Mo, V and W as alloy additives is

definitely much less common. These elements tend to form with each other the solutions of unlimited solubility, e.g. Cr-V, Cr-Mo or Mo-V [11-13], but are either totally insoluble in solid state aluminium or their solubility is very poor [14-16]. The consequence is formation of intermetallic compounds in the silumin microstructure that tend to increase the alloy brittleness. Silumins crystallizing at a relatively low heat dissipation rate (cast in sand and ceramic moulds) are particularly exposed to this risk. Use of metal moulds makes the crystallization of fine-grained non-equilibrium phases or saturation of a solid solution possible. This can improve the selected properties of silumin. Studies in this field described in [17-20] lead to the conclusion that the addition of high melting point elements can increase the tensile

strength R_m and unit elongation A . This is probably related to supersaturation of a solid $\alpha(\text{Al})$ silumin solution with high melting point additives. For example, to obtain in the silumin an elongation of $A = 6.0\%$, the best content of these elements is 0.05-0.15% Cr, 0.05% or 0.15% Mo, 0.05% V and 0.15% W.

The aim of this study is to discuss results of statistical analysis of the impact of Cr, Mo, V and W content on tensile strength R_m , elongation A and HB of silumins using data derived from the full range of combinations of these elements.

2. Research methodology

The silumin with the chemical composition range given in Table 1 was used as a base alloy.

Table 1.
Scope of the chemical composition of the investigated initial silumin grade EN AC-46000

Chemical composition, wt%									
Si	Cu	Zn	Fe	Mg	Mn	Ni	Ti	Cr	Al
8.69	2.09	0.90	0.82	0.21	0.18	0.05	0.042	0.023	
÷	÷	÷	÷	÷	÷	÷	÷	÷	balance
9.35	2.43	1.07	0.97	0.32	0.25	0.13	0.049	0.031	

This is the alloy with composition similar to EN-AC 46000, which means a typical hypoeutectic silumin used for pressure die casting. The silumin characterized by the chemical composition given in Table 1 was melted in a gas-heated shaft furnace. In this furnace, it was refined with an Ecosal Al 113.S solid refiner. Then, the silumin was tapped to a pouring ladle, in which it was deslagged and transported to a holding furnace set up at a pressure die casting machine with the horizontal IDRA 700S pressing chamber. In the holding furnace, Cr, Mo, V and W additives were introduced to the silumin. Due to a relatively high melting point of these elements and a relatively low temperature of the silumin in the holding furnace dictated by the technological regime of the process, the tested additives were introduced in the form of AlCr15, AlMo8, AlV10 and AlW8 master alloys. High melting point additives were introduced to the silumin individually, i.e. each element separately, and in various combinations. The following combinations were used:

- binary systems: CrMo, CrV, CrW, MoV, MoW and VW,
- ternary systems: CrMoV, CrMoW, CrVW and MoVW,
- quaternary systems (all tested elements added at the same time).

The applied master alloys were added to the silumin in an amount sufficient to obtain the required content of high melting point additives in individual melts. When the high melting point additives were added to the silumin as individual elements, their content varied from 0.0% to 0.5% with the increment of 0.1% in subsequent melts. In the case of melts in which more than one high melting point element was used, the content of all high melting point elements in the silumin was uniform. In binary combinations, the content of each of the high melting point elements varied in the range of 0.0% to 0.4%. The increment in the content of the examined elements in subsequent melts was 0.1%. In the case of ternary and quaternary combinations, the

range of variability in the content of the high melting point additives was 0.00 - 0.25% and the increment was 0.05%.

For all variants of the chemical composition, pressure die castings of the side cover of the roller shutter casing were made. The shape of this casting resembles a plate with a wall thickness $g = 2$ mm.

To determine the selected properties of silumin, static tensile tests and Brinell hardness measurements were made. The tensile strength R_m and the unit elongation A were determined in the static tensile test carried out on an Instron 3382 testing machine at a speed of 1 mm/min. The tensile strength of silumin was determined on samples taken from the pressure die castings. From one pressure die casting, three test samples were taken for each of the examined chemical compositions of the silumin. The samples had a flat shape with a rectangular cross-section of 10×2 mm recommended by the standard [21]. Hardness HB was measured with an HPO 2400 universal hardness tester. The following measurement parameters were applied: ball diameter $d = 2.5$ mm, load of 613 N, and static load duration of 30 seconds.

As a statistical tool for the evaluation of the main effects of Cr, Mo, V and W content in the examined silumin on the level of tested mechanical properties, the ANOVA analysis of variance was used. Examples of this use of ANOVA are given in [22-24].

The database was created in the Excel spreadsheet, while statistical calculations were made using licensed packages, such as Statistica v. 7.1.PL from Statsoft and MedCalc Statistical Software v.14.10.2 (MedCalc Software bvba, Ostend, Belgium).

3. Test results

As part of the research work, a database for statistical analysis was created. The analysis covered the effect of high melting point additives, i.e. Cr, Mo, V and W, on tensile strength R_m , elongation A and HB of pressure die cast silumin. The aim of the analysis was to determine effect of, and to what extent these additives can affect the level of the tested silumin properties, optimizing next their content to obtain higher values.

In all statistical analyses, the significance level (type I error) was set at $p(\alpha) = 0.05$.

3.1. Database for statistical analysis

The database for statistical analysis consists of independent (explanatory) variables and dependent (response) variables. The independent variables are the tested high melting point additives, expressed as percent variable concentrations of elements, such as Cr, Mo, V and W. The dependent variables are the results of measurements of the tensile strength R_m [MPa], elongation A [%] and HB of the tested silumin.

The developed database contains both independent and dependent variables related to the silumin containing 15 combinations of high melting point additives and the silumin which is free from these additives. It comprises values of independent and dependent variables for 69 pressure die castings made from silumin containing high melting point additives and 4 castings made from the base (initial) silumin. Three samples were

taken from each casting to perform a static tensile test. So, the database includes 207 results of the R_m , A and HB measurements obtained for the silumin with the addition of high melting point elements and 12 results obtained for the base silumin.

The effect of Cr , Mo , V and W additives on the proof stress $R_{p0.2}$ was discussed in an earlier study [25]. However, the results of the statistical analysis regarding the impact of Cr , Mo , V and W on R_m ; $R_{p0.2}$; A and HB are presented in [26].

This article presents the results of multiple regression analysis for a standardized variable that captures the results of the studied properties, because it had to be determined the amount of Cr , V , W and Mo so as to obtain the highest possible properties (R_m , $R_{p0.2}$, HB and A) taken together. The article also justifies the choice of proper statistical methodology (i.e. ANOVA-based analysis), since the data in the article show that the regression analysis only includes the LINEAR EFFECT. The elements studied are not characterized by such influence.

For the purpose of statistical analysis, independent variables were recoded into qualitative variables Cr_I , Mo_I , V_I and W_I (called factors), which had nine levels (from 1 to 9) depending on the content of high melting point additives in the silumin, i.e. 0.00% = 1; 0.05% = 2; 0.10% = 3; 0.15% = 4; 0.20% = 5; 0.25% = 6; 0.30% = 7; 0.40% = 8; 0.50% = 9.

Dependent variables were also included in the database in the form of standardized values. The standardized values of tensile strength R_m [MPa], elongation A [%] and HB were designated in the database as $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$, respectively, and were determined from the following relationships:

$$Sost_{R_m} = (R_m - SR_{R_m}) / \sigma_{R_m} \quad (1)$$

$$Sost_A = (A - SR_A) / \sigma_A \quad (2)$$

$$Sost_{HB} = (HB - SR_{HB}) / \sigma_{HB} \quad (3)$$

were:

- $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$ - standardized value of tensile strength, elongation and hardness [-], respectively,
- R_m , A and HB – empirical value of tensile strength [MPa], elongation [%] and hardness HB , respectively,
- SR_{R_m} , SR_A and SR_{HB} – mean value of tensile strength [MPa], elongation [%] and hardness HB , respectively,
- σ_{R_m} , σ_A , and σ_{HB} – standard deviation of tensile strength [MPa], elongation [%] and hardness HB , respectively,

By the transformation of dimensional variable, the standardization enables obtaining a dimensionless variable. The characteristic feature of standardized quantity is that it has a mean of zero and a standard deviation of one. The standardized variables were used to optimize the effect of high melting point additives in the examined silumin on the values of dependent variables.

For samples of the base silumin, the mean values of dependent variables were $R_m = 247$ MPa ($\sigma_{R_m} = 28.1$ MPa); $A = 3.5\%$ ($\sigma_A = 1\%$) and $HB = 115$ ($\sigma_{HB} = 3.1$).

3.2. Evaluation of the effect of the content of Cr , Mo , V and W on $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$

The analysis of variance (ANOVA) was used to evaluate the main effects of Cr , Mo , V and W content in silumin on dependent variables $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$. As factors in the analysis of variance were adopted the values of the content of the tested alloy elements in silumin (Cr , Mo , V and W) coded with numbers from 1 to 9.

The effect of Cr , Mo , V and W content in the tested silumin on its R_m , A , and HB was optimized to obtain the maximum values of standardized dependent variables $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$.

To determine the optimum level (content) of the examined input factor, the basic characteristics of descriptive statistics of the values of dependent variables $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$ were estimated for each of the tested levels of each significant factor and post-hoc LSD tests were conducted.

3.2.1. Analysis of the effect of Cr_I , Mo_I , V_I and W_I factors in the silumin on $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$

Table 2 compares the results of statistical evaluation of the effect of Cr_I , Mo_I , V_I and W_I variables, i.e. factors corresponding to chromium, molybdenum, vanadium and tungsten content in the silumin, respectively, on standardized dependent variables $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$.

Table 2.

The results of statistical evaluation of the effect of Cr_I , Mo_I , V_I and W_I factors in silumin on $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$

ANOVA of main effects. Dependent variable:						
Parameter	$Sost_{R_m}$		$Sost_A$		$Sost_{HB}$	
	F	p	F	p	F	p
Constant	0.0885	0.7663	1.7187	0.1914	28.8128	<0.0001
Cr_I	1.8022	0.0789	1.5863	0.1313	8.9335	<0.0001
Mo_I	2.3547	0.0195	2.4734	0.0143	3.2423	0.0018
V_I	4.4841	0.0001	3.5157	0.0008	3.0813	0.0028
W_I	2.14035	0.0341	2.0140	0.0469	2.1846	0.0304
Bartlett's test:	p = 0.0563		p = 0.4481		p = 0.0673	
Shapiro-Wilk test ¹ :	p = 0.0650		p = 0.1217		p = 0.0726	
Shapiro-Wilk test ² :	p = 0.0941		p = 0.0848		p = 0.0743	

¹Verification of the agreement of the distribution of the examined target feature with the normal distribution

²Verification of the agreement of the distribution of residues with the normal distribution

To check the basic assumption about the homogeneity of variance in all studied groups (levels of factors studied), Bartlett's test was used. It was found that the examined variances were homogeneous for all the analyzed variables, i.e. $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$, and the analysis could go on. Another reason for using the ANOVA test results disclosed in Table 2 was to check the compatibility of the distribution of the examined output characteristics, i.e. $Sost_{R_m}$, $Sost_A$ and $Sost_{HB}$, with the normal distribution and the compatibility of the distribution of residues with the normal distribution. The results of Shapiro-Wilk tests confirmed the compatibility of the distribution of the examined resultant features and residues with the normal distribution.

As regards the main effects, the results of ANOVA indicate that:

- for the examined levels of Mo_1 , V_1 and W_1 factors, the mean values of $Sost_{Rm}$ (the standardized value of tensile strength R_m) differ in a statistically significant way (p: 0.0196, 0.0001, 0.0341, respectively). Thus, the examined input variables Mo, V and W (recoded into factors) significantly affect the resultant variable $Sost_{Rm}$,
- for the examined levels of Mo_1 , V_1 and W_1 factors, the mean values of $Sost_A$ (the standardized value of elongation A) differ in a statistically significant way (p: 0.0143, 0.0008, 0.0469, respectively). Thus, the examined input variables Mo, V and W (recoded into factors) significantly affect the resultant variable $Sost_A$,
- for the examined levels of Cr_1 , Mo_1 , V_1 and W_1 factors, the mean values of $Sost_{HB}$ (the standardized value of hardness HB) differ in a statistically significant way (p: <0.0001, 0.0018, 0.0028, 0.0304, respectively). Thus, the examined input variables Cr , Mo , V and W (recoded into factors) significantly affect the resultant variable $Sost_{HB}$.

3.2.2. Analysis of the effect of Cr_1 factor in the silumin on $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$

Figure 1 shows the results of studies of the effect of Cr_1 factor, i.e. chromium content, on standardized dependent variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$. The recommended levels of the examined factor to obtain the maximum value of a given property are indicated in a grey colour. This approach for determining the highest values of individual properties was also adopted in other drawings included in the article.

Factor	Level of the factor	$Sost_{Rm}$ Mean	$Sost_{Rm}$ SD	$Sost_A$ Mean	$Sost_A$ SD	$Sost_{HB}$ Mean	$Sost_{HB}$ SD
Cr_1	1 (0.00%)	-0.2280	1.1189	-0.2533	1.0090	0.3025	0.8870
Cr_1	2 (0.05%)	0.7865	0.8050	0.5870	0.9931	0.6754	0.8341
Cr_1	3 (0.10%)	0.7016	0.9382	0.5703	0.9085	0.0239	0.6047
Cr_1	4 (0.15%)	0.4013	0.5483	0.8351	0.7577	-0.6669	0.4620
Cr_1	5 (0.20%)	-0.2438	0.5542	0.1775	0.78071	-0.0545	0.9898
Cr_1	6 (0.25%)	-0.2214	0.6307	0.0911	1.1218	-1.0435	1.0988
Cr_1	7 (0.30%)	-0.2001	0.5821	-0.4005	0.6405	-0.2381	1.2815
Cr_1	8 (0.40%)	-0.3429	0.5762	-0.2374	0.9021	-0.9652	0.8101
Cr_1	9 (0.50%)	-1.0496	0.5220	-0.3749	0.4675	-1.6923	0.3001

Fig. 1. Evaluation of selected characteristics of descriptive statistics of the standardized variables values $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$ for the factor Cr_1

The data show that to obtain the best value of standardized variable $Sost_{Rm}$, content of chromium in the tested silumin should be at the level of 0.05-0.10% Cr; to obtain the best value

of standardized variable $Sost_A$ at the level of 0.05-0.15% Cr, and to obtain the best value of standardized variable $Sost_{HB}$ at the level of 0.05% Cr.

For each of the examined standardized variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$, the results of post-hoc LSD tests indicated a number of statistically significant differences between individual groups differing in the level of factor Cr_1 .

3.2.3. Analysis of the effect of Mo_1 factor in the silumin on $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$

Figure 2 shows the results of studies of the effect of Mo_1 factor, i.e. molybdenum content in silumin, on standardized dependent variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$.

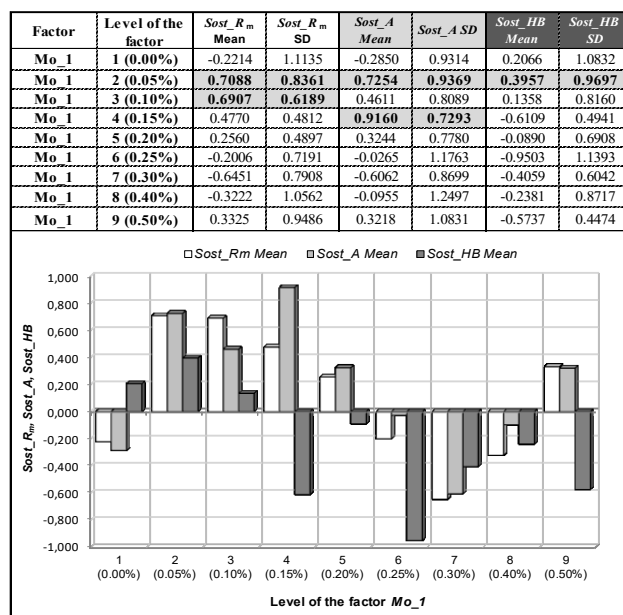


Fig. 2. Evaluation of selected characteristics of descriptive statistics of the values of standardized variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$ for the factor Mo_1

The data show that to obtain the best value of standardized variable $Sost_{Rm}$, molybdenum content in the tested silumin should be at the level of 0.05-0.10% Mo; to obtain the best value of standardized variable $Sost_A$ at the level of 0.05 or 0.15% Mo, and to obtain the best value of standardized variable $Sost_{HB}$ at the level of 0.05% Mo.

For each of the examined standardized variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$, the results of post-hoc LSD tests indicated a number of statistically significant differences between individual groups differing in the level of factor Mo_1 .

3.2.4. Analysis of the effect of V_1 factor in the silumin on $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$

Figure 3 shows the results of studies of the effect of V_1 factor, i.e. vanadium content in silumin, on standardized dependent variables $Sost_{Rm}$, $Sost_A$ and $Sost_{HB}$.

The data show that to obtain the best value of standardized variable $Sost_{Rm}$, vanadium content in the tested silumin should be at the level of 0.05-0.10% V; to obtain the best value of

standardized variable *Sost_A* and the best value of standardized variable *Sost_HB* at the level of 0.05% Mo.

For each of the examined standardized variables *Sost_R_m*, *Sost_A* and *Sost_HB*, the results of post-hoc LSD tests indicated a number of statistically significant differences between individual groups differing in the level of factor *V₁*.

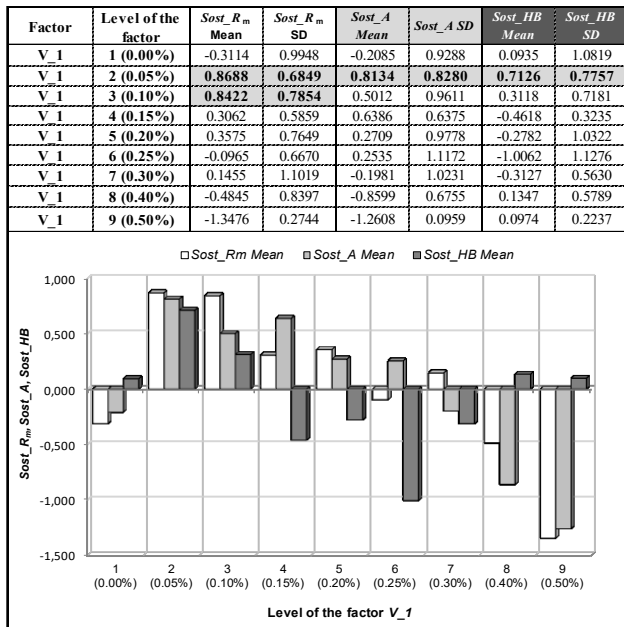


Fig. 3. Evaluation of selected characteristics of descriptive statistics of the values of standardized variables *Sost_R_m*, *Sost_A* and *Sost_HB* for the factor *V₁*

3.2.5. Analysis of the effect of *W₁* factor in the silumin on *Sost_R_m*, *Sost_A* and *Sost_HB*

Figure 4 shows the results of studies of the effect of *W₁* factor, i.e. the content of tungsten in silumin, on standardized dependent variables *Sost_R_m*, *Sost_A* and *Sost_HB*.

The data show that to obtain the best value of standardized variable *Sost_R_m* tungsten content of in the tested silumin should be at the level of 0.05-0.10% W; to obtain the best value of standardized variable *Sost_A* at the level of 0.15% W, and to obtain the best value of standardized variable *Sost_HB* at the level of 0.50%.

For each of the examined standardized variables *Sost_R_m*, *Sost_A* and *Sost_HB*, the results of post-hoc LSD tests indicated a number of statistically significant differences between individual groups differing in the level of factor *W₁*.

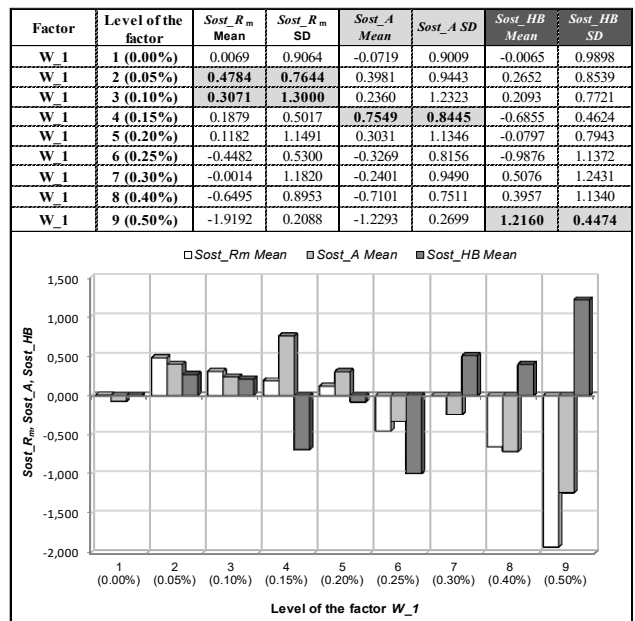


Fig. 4. Evaluation of selected characteristics of descriptive statistics of the values of standardized variables *Sost_R_m*, *Sost_A* and *Sost_HB* for the factor *W₁*

4. Conclusions

The data contained in the paper predispose to the following conclusions:

- each of the examined high melting point additives introduced to the silumin in an appropriate amount can improve the silumin properties, i.e. *R_m*, *A* and *HB*;
- to obtain *high tensile strength R_m* in the tested silumin, the content of each of the high melting point additives should be in the range of 0.05-0.10%, then the standardized mean value *Sost_R_m* will be equal to ~ 1.32, i.e. to about 291 MPa, at a standard deviation of 9.89 MPa. The largest impact on the increase in *R_m* has vanadium in the amount of 0.05-0.10%.
- to obtain *high elongation A* in the tested silumin, chromium content should be in the range of 0.05-0.15%, the molybdenum content should be equal to 0.05% or 0.15%, vanadium to 0.05% and tungsten to 0.15%, then the standardized mean value *Sost_A* will be equal to ~ 1.5, i.e. to about 6%, at a standard deviation of 0.93%. The largest impact on the increase in *A* has molybdenum in the amount of 0.15%.
- to obtain *high hardness HB* in the tested silumin, chromium, molybdenum and vanadium should amount to about 0.05%, and tungsten to about 0.5%, then the standardized mean value *Sost_HB* will be equal to ~ 1.29, i.e. to about 117 HB, at a standard deviation of 1.63. The largest impact on the increase in *HB* has tungsten in the amount of 0.5%.

Acknowledgements

Project financed from means of the National Centre for Research and Development in years 2013 ÷ 2015 as project UDA-POIG.01.04.00-10-079/12.

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